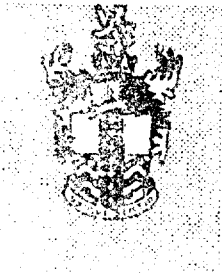AD-A233 633

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RSRE
MEMORANDUM No. 4454

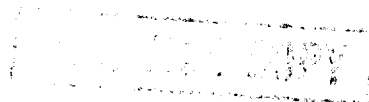# ROYAL SIGNALS & RADAR ESTABLISHMENT

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SILICON AVALANCHE PHOTODIODE
ACTIVE-QUENCHING CIRCUIT

Authors: M Johnson & R Jones

**PROCUREMENT EXECUTIVE,
MINISTRY OF DEFENCE,
RSRE MALVERN,
WORCS.**

RSRE MEMORANDUM No. 4454

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Royal Signals and Radar Establishment
Memorandum 4454

Title: Silicon Avalanche Photodiode Active-Quenching Circuit

Authors: M Johnson and R Jones

Date: December 1990

Summary

Research has shown that actively-quenched
silicon avalanche photodiodes (APD) can be
successfully operated throughout the
visible region. Two patented circuits exist
which have been assembled as printed
circuit board prototypes.

A silicon hybrid of the most recent
circuit, having two independent channels,
has been demonstrated to operate at a
photon counting rate in excess of 40 MHz.
If the APD's are cooled a dynamic range
approaching that of the average
photomultiplier tube is possible. Two
problems with the hybrid circuit have been
identified and a way forward to eliminate
the problems is proposed.

Silicon Avalanche Photodiode Active-Quenching Circuit

INTRODUCTION:
Until recently most high-speed photon counting measurements
incorporated a photomultiplier tube (PMT) for photon detection.
On average, when a photon is detected a photo-electron is
ejected from the photocathode of the PMT with an efficiency
known as the quantum efficiency; this ratio of photo-electrons
to photons is usually less than 6%. Even for the best PMT this
quantum efficiency has a peak of about 17% and to obtain this
figure multiple passes of the photocathode material are
required. This can be accomplished using specially designed
optical elements. Another characteristic of interest is the
dynamic range of operation within which photon counting
performance can be expected. PMT's can be manufactured which
provide a photon counting rate in excess of 250 MHz, while they
can be cooled to about -20 $^\circ$C to obtain a 'dark count rate' as
low as 1 count per hour. In general a good photon counting PMT
will have a dynamic range in excess of 10^6.

The emergence of the semi-conductor Avalanche Photodiode (APD)
[3] promised detection systems with a much higher quantum
efficiency; 90% could theoretically be envisaged. To operate an
APD as a photon counting detector it is necessary to reverse
bias it for operation in the so called 'Geiger' mode [1]
(although 'sub-Geiger' operation has been demonstrated). In
this mode the APD is biased at some level above the voltage at
which a photon detection will trigger a micro-plasma avalanche
(the Geiger threshold). During this avalanche the diode takes
on a relatively low impedance state which, if not arrested, can
result in self-destruction. The avalanche can be extinguished
(quenched) by reducing the bias voltage significantly below the
Geiger threshold.

PASSIVE QUENCHING:
The quenching operation can be accomplished in two ways.
Firstly, as shown in Fig. 1, the diode is passively quenched
[1]. In this mode the diode is reverse biased about 10 volts
above its Geiger threshold. The bias is applied through a large

series resistor, 200 Kohms for example, and the avalanche
current results in a small negative step across the 50 ohm
resistor. As the current through the large series resistor
increases the bias voltage across the diode sharply decreases.
This quenches the avalanche and the voltage across the APD
increases exponentially towards ground as the self-capacitance
of the diode is charged through the large series resistor. This
simple configuration has a severely restricted maximum count
rate because the recharge time is lengthy. This simple system
can only be employed in systems requiring maximum photon
counting rates of up to 1 MHz and RCA market a cooled module of
this type.

One important lesson to be learnt from this configuration is
that, in order to achieve high quantum efficiencies, the device
must be operated at a bias voltage close to that capable of
producing a self-sustaining avalanche. The basis of the
research at RSRE has been the design of circuits to actively
quench the avalanche and to allow the APD to recharge, back to
its operating bias, passively. The passive recharge avoids the
APD being triggered by voltage transients generated by an
active circuit.

ACTIVE QUENCHING Mark I:
In RSRE Patent Application, No 8628110, one such example of an
active quenching circuit is described which extends the photon
counting rate to 20 MHz. This is achieved by detecting the
onset of avalanche as early as possible, quenching it by
reducing the voltage across the APD to below its Geiger
threshold, and subsequently allowing the APD to recharge to its
quiescent state through a ballast resistor while disabling the
circuit for a defined dead time. This technique can be
summarised as active quench with a passive reset [2]. The
minimum interval between output pulses is fixed by the dead
time so that correlation experiments will have a defined
counting loss and a minimum distortion due to 'odd/even'
affects. It is now considered however, that in this circuit,
the action of holding quench active for 50% of the total
detection cycle is prohibitive of optimum operation.

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ACTIVE QUENCH Mark II:
A new strategy for an active quench/passive reset circuit for APD's resulted in a second RSRE Patent Application, No 8915245.8.

The new design, shown in Fig. 2, reduces the quench portion of the detection cycle to a defined minimum which is independent of the dead time. This reduction is effected by using a high-speed comparator to detect the sufficient application of the quenching voltage. This results in a maximum photon counting rate in excess of 40 MHz.

The basic circuit consists of two high-speed comparators, C1 and C2, for detecting start and end times for quench, the quenching circuit, a pulse-shaping output circuit, and a dead-time circuit. The waveforms generated at nodes N1 to N4 of the circuit, including timing marks, are represented in Fig. 3.

When the circuit is in its quiescent state (before time t_1), ie. no photon detection, the operating point at node N1 is derived from the series combination of R2, R3, D3, and R7. The voltage at this point is designed to establish a voltage at node N2, the first input of comparator C1, such that its value is equivalent to a LOW comparator output. The node N2 voltage should therefore reverse bias D5 and allow N2 to change when required as a result of a photon detection. VR1 should be set at a voltage slightly less than N2, typically a difference of 50 mV, which drives the outputs of C1 to set the quench circuit OFF. Node N3 is therefore set by the series combination of R1 and D1 which reverse biases D2. The first input of comparator C2 is tapped off the junction of R2/R3 and VR2 on its second input defines the quench level. In the quiescent state the normal values for these inputs drive the comparator C2 outputs such that node N2 is unclamped, the dead-time circuit is OFF, and consequently C1 is enabled.

When the APD detects a photon at time t_1 and begins to avalanche, the rapid increase of current through the series

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combination R2 and R3 results in a voltage drop at node N1 and therefore also at node N2. The reduction at N2 forces the outputs of comparator C1 to change at time t_2 which turns the quench circuit ON. As current is drawn through R1 the voltage at node N3 falls. This transition is used by the output circuit to generate the leading edge of the output waveform. As N3 falls diode D2 becomes forward biased and current is also drawn through R2 and R3 (active quench). This results in a voltage drop at N1 which reverse biases diode D3, and node N2 is eventually clamped by the output of comparator C2 when diode D5 becomes forward biased. As node N1 continues to fall the voltage on the first input of comparator C2 is also reducing. This continues until the quench setting on VR2 is reached, when the outputs of comparator C2 at time t_3 change and force the voltage at node N2, through diode D5, to increase. This increase is sufficient to return the outputs of comparator C1 to their quiescent state thereby turning the quench circuit OFF. Comparator C2 also triggers the dead time circuit at this point and, due to the change of state at node N4 at time t_4, disables comparator C1 for the remainder of the cycle. When the quench circuit is turned OFF node N3 at time t_5 begins to return to the voltage set by R1 and D1. This transition is used by the output circuit to generate the trailing edge of the output waveform. At this point diodes D2 and D3 are both reverse biased and node N1 returns to its quiescent state by recharging the capacitance associated with the APD through R2 and R3 (passive reset). As this occurs the outputs of comparator C2 return to their quiescent state and finally, after node N1 at time t_6 has reached its final value and diode D3 is once again forward biased, node N4 at time t_7 returns to its quiescent state enabling comparator C1 ready for the next detection.

The circuit described above was considered to be a suitable candidate for the Fibre-linked Imaging Synthesis Telescope project (FIST). FIST requires detectors to be in groups of two with three such groups making up the initial system. A feasibility study into the realisation of a custom designed integrated circuit was carried out and, although found to be

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possible, the number of circuits required would not justify the cost. A hybrid device was therefore considered and a prototype design, with two independent APD quench circuits on a single substrate, was manufactured. Photographs of the hybrid and quench circuit waveforms for the two channels are shown in Figs. 4 and 5 respectively. In order to guard against external power supply fluctuations voltage regulators were included in the design for stabilising the voltages of critical nodes. The development was also considered a useful test of how independent the circuit is to the absolute value of its passive components.

After initial component failures were replaced both channels could be made to operate satisfactorily but two problems were high-lighted. Firstly, the substrate temperature exceeded the maximum operating temperature of some of the circuits active components. The regulators used were primarily responsible as the main dissipative elements. Their internal dissipation was coupled to the substrate which caused an unexpected (because of inadequate and incomplete package specification) temperature rise of the whole device. In order, therefore, to enable any further tests to be done it was decided to temporarily by-pass the regulators in the circuit and supply adequately stabilised voltages from external power supplies.

Secondly, when both circuits of the hybrid were operating at the same time it was evident that there was some cross-channel interference indicating that a modified track routing and component layout would be required. All tests have been done using uncooled APDs' although preliminary experimentation with cooling systems has shown that a Peltier system, providing a 40 degree differential, could be successfully demonstrated. It is anticipated that if such cooling were to be employed with the current APD quenching circuit a dynamic range of the order of 10^5 could reasonably be expected for the system. No measurements of APD quantum efficiency have been carried out with this prototype.

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FURTHER WORK:

It is proposed that consideration will be given to eliminating the over heating and crosstalk problems of the dual circuit hybrid. However, it is clear that a hybrid containing a single APD quenching circuit would not only be easier to manufacture but would have a wider commercial applicability. Steps will be taken to attempt some characterisation with regard to quantum efficiency on any improved circuit implementation.

REFERENCES:

1/ R G W Brown, J G Rarity, K D Ridley, *Characterisation of Silicon Avalanche Photodiodes for Photon Correlation Measurements, 1. Passive Quenching,* App. Opt. 25, 4122 (1986).

2/ R G W Brown, R Jones, J G Rarity, K D Ridley, *Characterisation of Silicon Avalanche Photodiodes for Photon Correlation Measurements, 2. Passive Quenching,* App. Opt. 26, 2383 (1987).

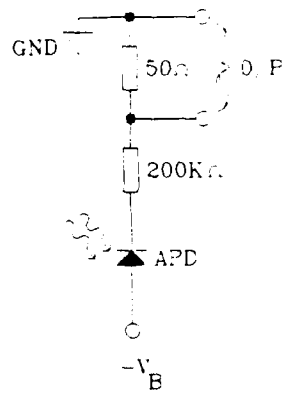3/ RCA Data Sheet, C30921S Silicon Avalanche Photodiodes, May 1984.
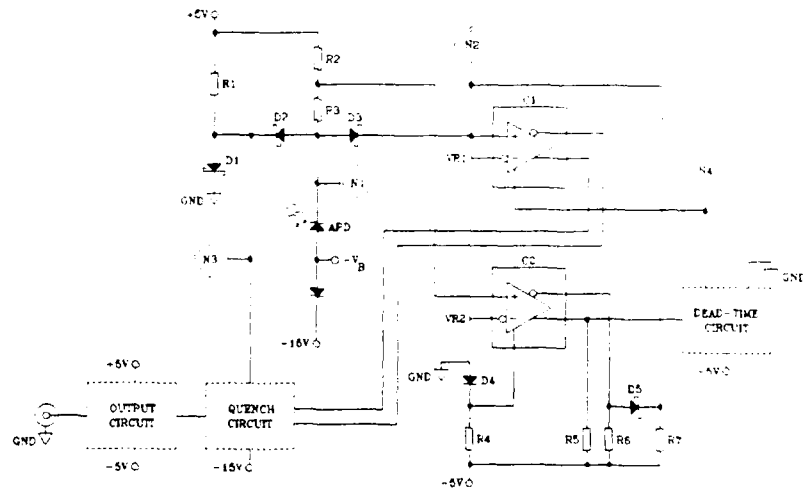
Fig. 1 - Passively Quenched APD Circuit
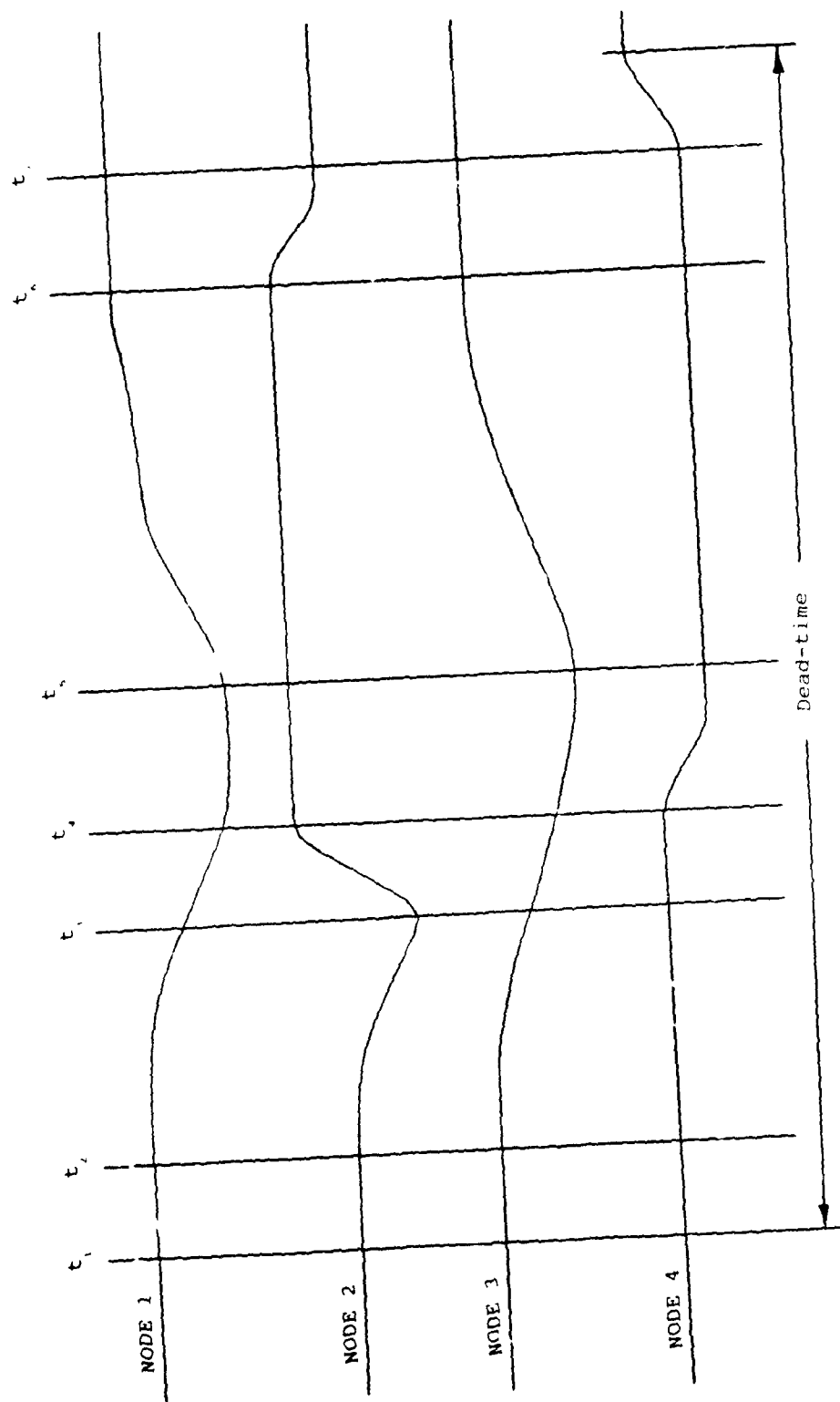

Fig. 2 - Actively Quenched APD Circuit

Fig. 3 — Timing Diagram (Amplitudes are unscaled)

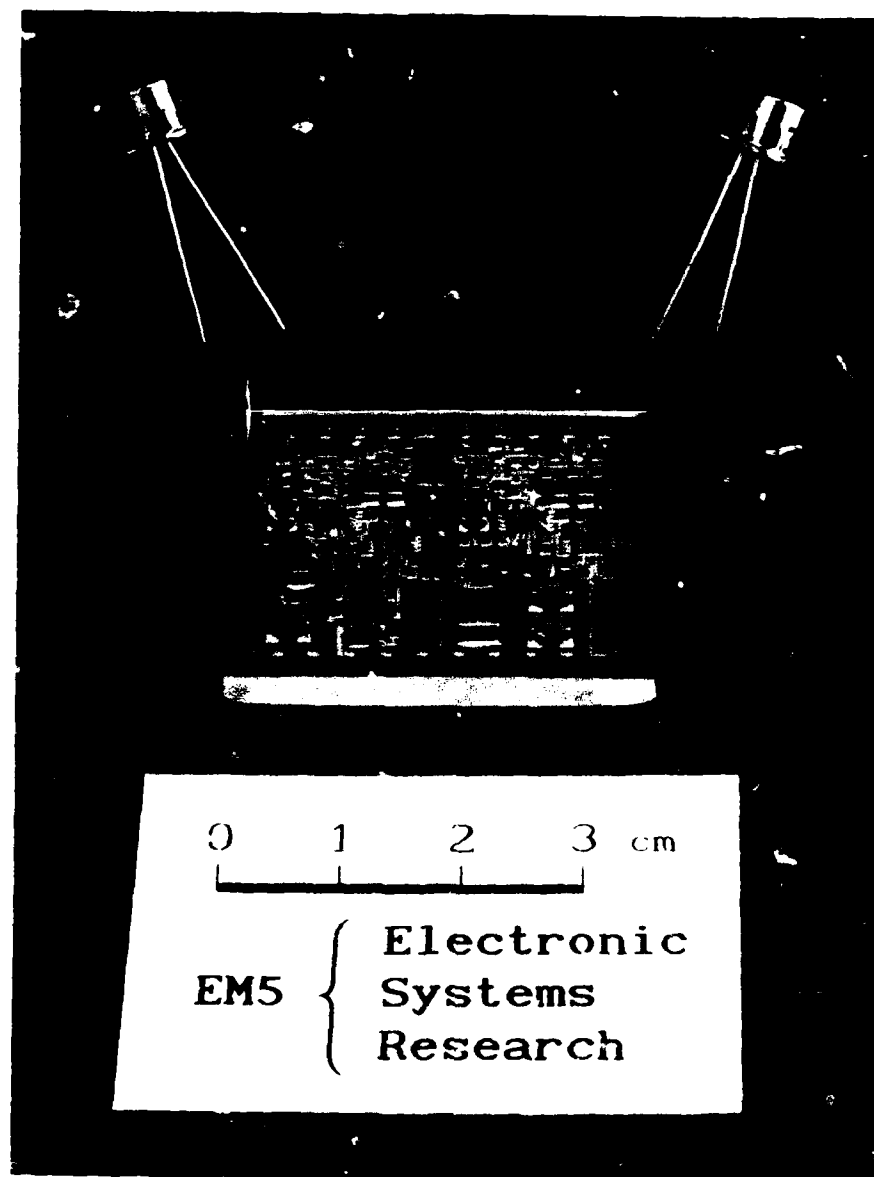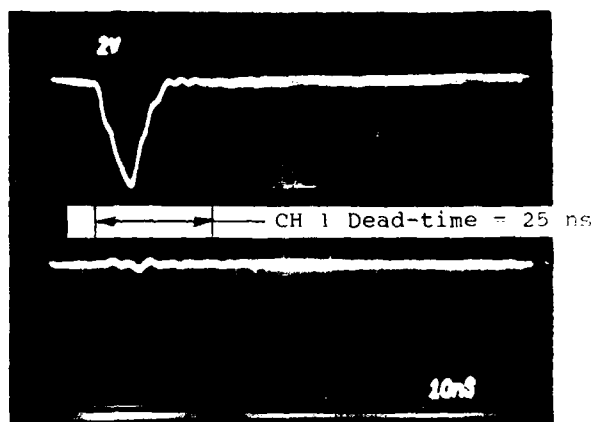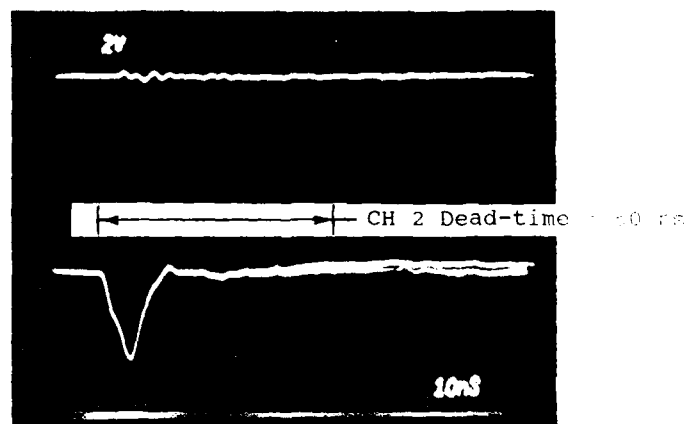Fig. 4 - Photograph of Hybrid Two-channel APD Quenching Circuit

Node N1 of each channel
(triggered on channel 1)

CH 1 Dead-time = 25 ns

Node N1 of each channel
(triggered on channel 2)

CH 2 Dead-time = ≤0 ns

Node N1 of channel 1 and
its corresponding output
(triggered on channel 1)
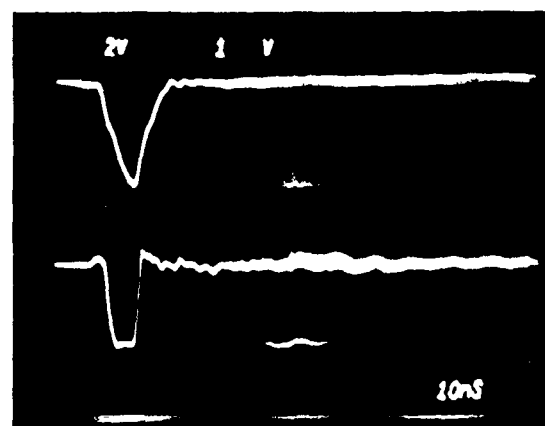
Fig. 5 - Photographs of Hybrid APD Quenching Circuit Waveforms

REPORT DOCUMENTATION PAGE

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Monitoring Agency Name and Location

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Agency Reference	Contract Number and Period

Project Number	Other References

Authors JOHNSON, M; JONES, R	Pagination and Ref 10

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Descriptors

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